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TRAJECTORY OPTIONS FOR ICE AND FIRE PREPROJECT MISSIONS UTILIZING SOLAR ELECTRIC PROPULSION

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ABSTRACT

The Ice and Fire Preproject defined the first mission set of the Outer Planets/Solar Probe Program consisting of the Europa Orbiter, Pluto-Kuiper Express, and Solar Probe missions. The development of low cost, high performance spacecraft and propulsion systems, in conjunction with the desire to minimize launch vehicle requirements, has been a tremendous challenge. Recent developments in one area of propulsion, Solar Electric Propulsion (SEP), may provide a stepping stone to advanced propulsion systems for future missions. Preliminary mission design software was used to discover and analyze SEP trajectories for the Ice and Fire missions. Potential benefits to the delivered spacecraft mass, in conjunction with the use of small, low cost launch systems, were examined. Unfortunately, the constraint on solar distance limits the benefits of SEP for outer solar system missions. Also, the requirement of a large bi-propellent propulsion system for Europa Orbiter, in addition to the SEP system, strongly reduces any potential benefits. SEP may offer potential benefits for Pluto-Kuiper Express and Solar Probe, but at the cost of system complexity. Although the current technology may not provide benefit for these particular missions, the potential of SEP, and electric propulsion in general, for other future missions is significant.

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INTRODUCTION

In the current National Aeronautics and Space Administration (NASA) budget plan, there exists a new proposed program aimed at opening the outer solar system to new robotic science missions. This program is called the Outer Planets / Solar Probe Program and is currently planned to begin in fiscal year 2000[1]. The first mission set of this program, the Ice and Fire missions, includes three very challenging missions which are sure to set the standard for future missions to the outer solar system: Europa Orbiter, Pluto-Kuiper Express, and Solar Probe.

(NOTE: Since the submission of this paper, the Ice and Fire Preproject has gained project status and is now called the Outer Planets / Solar Probe Project.)

The Outer Planets / Solar Probe Program will make use of the latest technology in order to develop low cost, high performance spacecraft . The NASA sponsored Advanced Deep Space System Development Program (ADSSDP, often referred to as X2000) is chartered to develop this technology, in conjunction with industry partners. This program will focus on advanced avionics, integrated microsystems, and advanced power systems. This technology will provide the foundation upon which missions to the outer solar system will rely for developing spacecraft to be sent to these new and exciting destinations. The Ice and Fire missions plan to make use of these developments by flying the same avionics and core software on all three missions.

In following with the philosophy of "faster, better, cheaper", missions to the outer solar system pose many difficult challenges, including those of extended lifetime, severe radiation environments, telecommunications and operations over long distances, and spacecraft autonomy. Probably the most difficult challenge is in the development of low cost, high performance propulsion systems, which are required for some of these missions, in conjunction with the desire to minimize launch vehicle costs. There have been recent developments in one area of propulsion which may in fact provide a stepping stone to advanced high performance propulsion systems in the future: Solar Electric Propulsion (SEP).

For years, small SEP systems have been used on Earth orbiting spacecraft for stationkeeping. The first interplanetary spacecraft to rely on SEP as its primary propulsive source is Deep Space 1 (DS1), which is scheduled to launch in October 1998. DS1, the first launch of the New Millennium Program, will use SEP to send a spacecraft by an asteroid and possibly a comet. This mission will use technology developed under the NASA SEP Technology Application Readiness (NSTAR) program. Work is also underway to build upon the NSTAR technology and develop a multi-engine SEP module for use on the Champollion / DS4 mission which is planning to launch in 2003. The goals of this mission are to rendezvous with a comet, map the surface, send a lander to the surface, and demonstrate the collection of a sample. These two missions will help validate this new technology and lead to further low cost developments in the area of electric propulsion. SEP may provide new mission options which allow for higher net spacecraft mass and/or lower launch vehicle performance requirements (thus lowering the cost of the launch system), as compared to conventional chemical propulsion options.

ASSUMPTIONS AND GUIDELINES

One of the main advantages of SEP is that nearly continuous thrust can be provided to the spacecraft at a very high specific impulse, thus resulting in a large Δv capability for a relatively low propellent mass. Several different types of trajectories, including those with various sequences of planetary gravity assists, have been analyzed for the Ice and Fire missions. Highly efficient ion engines along with gravity assists can be a potent combination for maximizing net spacecraft mass and/or enabling the use of a relatively small, inexpensive launch vehicle.

The preliminary mission design software used in this study to discover and analyze the SEP trajectories simultaneously integrates the equations of motion and the costate or variational equations. A two-point boundary value problem is solved to satisfy terminal constraints and targeting conditions. A more detailed description of the program can be found in Reference 2.

This software does have a limitation in that it only allows for at most two intermediate planetary flybys. However, this did not pose a significant problem for this study. In the cases where three intermediate flybys are required, the third body turns out to be always Jupiter. Assuming a reasonable solar array efficiency and size, the power available to the ion engines is below minimum operational levels long before reaching Jupiter (beyond ~ 3 A.U.). Therefore, in those cases (for Pluto-Kuiper Express and Solar Probe) where Jupiter was the third planetary flyby, the Jupiter encounter was assumed to be the endpoint of the trajectory as far as the software was concerned. At that point, a simple V_∞ matching routine was run, using the end conditions provided by the SEP software, and the trajectory was propagated out to the final body.

The SEP engines are modeled by approximating the thrust and mass flow rate as polynomial functions of the power available from the solar arrays. Measurements of these characteristics for the NSTAR 30 cm ion thruster (similar to the one to be flown on DS1) have been made at the NASA Lewis Research Center [3] and at the Jet Propulsion Laboratory.[4] Although there are plans to enhance the performance of this type of thruster for missions after DS1, the characteristics based on the current thruster are used for the analysis presented in this paper.

The trajectories described in this paper share several common SEP system assumptions. The thrusters can operate individually or in pairs with at most two thrusters operating simultaneously. During the thrusting periods, the engines are assumed to operate with a 90% duty cycle (on for 90% of the time). The remaining 10% of the time can be used for spacecraft operations, which require the engines to be off. The Delta II 7925 launch vehicle and a 7% performance contigency was assumed. Of the total power generated by the solar arrays, 100 watts is dedicated to the spacecraft, and the remaining power is available to the SEP engines. A 10% margin was also added to the deterministic Xe propellent load required for the mission. Also, all trajectories assumed the same NSTAR ion engine characteristics as stated above.These assumptions hold for each trajectory case, unless otherwise specified.

Europa Orbiter

The current reference mission for Europa Orbiter is a conventional direct trajectory to Jupiter launching in November 2003 and arriving at Jupiter in February 2007. One launch system under consideration for this option is the Space Shuttle (STS) with an IUS (Inertial Upper Stage) and a Star-48V kick stage. This trajectory does require a deterministic maneuver on the order of 100 m/s about one year post-launch. Other maneuvers, such as launch injection clean-up and navigation, are also required, as with all planetary missions. Once the spacecraft arrives at Jupiter, the bi-propellent propulsion system will be used to inject first into Jupiter orbit, and then eventually into Europa orbit about 2 years after Jupiter arrival. The mission design will take advantage of a variety of techniques in order to minimize the Δv requirements for these phases. However, even with these techniques, the requirements may still be as high as 2.5 km/s [5]. As stated above, SEP is no longer effective at this range, therefore, conventional propulsion is still required. A current estimate of the Europa Orbiter wet spacecraft mass, including a bi-propellent propulsion system, is on the order of 950 kg.

Pluto-Kuiper Express

For the Pluto-Kuiper Express mission, a Jupiter Gravity Assist (JGA), when available (2003, 2004, 2015, 2016, ...), can tremendously boost the performance of a mission by maximizing the possible net spacecraft mass and/or by minimizing the required flight time. Currently, the reference mission for Pluto-Kuiper Express is a ballistic JGA, launching in December 2004, with Pluto encounter anywhere from 8 to 16 years later, depending on the spacecraft mass and launch system. Launch systems under consideration for this mission include the Delta II 7925H/Star-30C and the Delta III/Star-48V. This trajectory requires only a small mono-propellent propulsion system to be used for navigation and attitude control. A current estimate of the Pluto-Kuiper Express wet spacecraft mass, including the mono-propellent propulsion system, is on the order of 225 kg.

Solar Probe

As with Pluto-Kuiper Express, the ballistic JGA trajectory offers very good performance for the Solar Probe mission. However, for Solar Probe, this opportunity occurs every Earth-Jupiter synodic period (about every 13 months) and is not constrained by geometry alignment to Pluto. The current reference mission for Solar Probe is a ballistic JGA, launching in February 2007 with the first perihelion pass scheduled for October 2010 and a second perihelion pass in January 2015. The launch system under consideration for this mission is the Delta III/Star-48V. A current estimate of the Solar Probe wet spacecraft mass, including the mono-propellent propulsion system and an advanced heat shield which also serves as the high-gain antenna, is very similar to that of the Pluto-Kuiper Express spacecraft at about 225 kg.

Common SEP Module Concept

As stated above, the SEP technology that would be used for the Ice and Fire missions is derived from the NSTAR program as well as the SEP system development underway by the DS1 and Champollion / DS4 missions. Some work was accomplished in the investigation of developing a common SEP stage that could be used for the Champollion / DS4, Europa Orbiter, Pluto-Kuiper Express, and Solar Probe missions. For the Ice and Fire missions, this stage would be jettisoned after it became no longer useful. In the case of Solar Probe, where the spacecraft actually does fall back into range of SEP effectiveness, the system must still be jettisoned due to the limited umbra during the planned 4 solar radii perihelion pass and probable contamination from the SEP system burn-up. Estimates for the dry mass of this stage were on the order of 400 kg, which includes solar arrays, 4 ion engines, and sufficient tank volume to hold about 400 kg of Xe propellent. (Although two engines at most can operate simultaneously, up to four engines are carried to alleviate lifetime and throughput concerns.) In addition, an estimated 50 kg would be required for the Europa Orbiter SEP stage to provide sufficient structure for supporting the larger spacecraft. Some additional mass may also be required to accommodate higher solar array power levels. However, for the purpose of this paper, this not considered.

RESULTS

A summary of several representative SEP trajectories, and their performance, for each of the Ice and Fire missions, is provided in Table 1.

Europa Orbiter

Several types of SEP trajectories to Jupiter were analyzed for the Europa Orbiter mission: direct from Earth to Jupiter with both more and less than one complete revolution around the Sun, single and double Venus gravity assists, Earth gravity assist, and Venus-Earth gravity assists. Trajectories which include an Earth gravity assist result in a higher net spacecraft mass, but Earth flybys may not be desirable, for reasons which are beyond the scope of this discussion. Therefore, at the time of this study, only the SeVVGA options looked as though they may provide

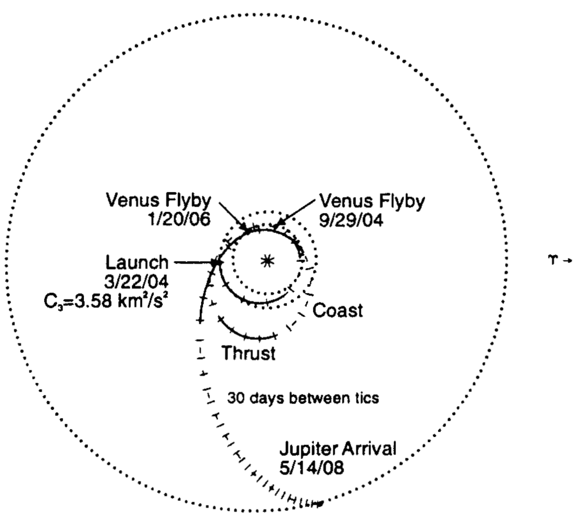

Figure 1 : Europa Orbiter 2004 SeVVGA Trajectory

*Table 1 : SEP Trajectory Performance Summary for Ice and Fire Missions**

Trajectory	Launch Date (dd-mmm-yy)	Flight Time[1] (yrs)	Power Level[2] (kW)	Net Spacecraft Mass[3] (kg)
Europa Orbiter				
SeVVGA	23-Jul-02	4.0	6	941 (1034)
SeEGA	13-Sep-02	4.3	6	959
SeDirect[4]	01-Dec-02	4.8	6	688
SeDirect[4]	01-Jan-04	4.8	6	697
SeVEGA	21-Mar-04	4.8	6	1018
SeVVGA	22-Mar-04	4.2	6	963 (1070)
SeEGA	08-Nov-04	4.0	6	974
SeVGA	04-Dec-04	4.0	6	784
Pluto-Kuiper Express				
SeEGA	24-Jan-02	9.5	5	463
SeVVJGA	13-Jul-02	11.9	6	<528>
SeVVJGA	04-Aug-02	8.5	6	526
SeVVJGA	15-Aug-02	9.1	6	668
SeJGA[5b]	10-Sep-02	10.2	11	520
SeEJGA[6]	07-Oct-02	10.2	6(?)	322
SeJGA[5a]	12-Nov-02	12.1	11	592
SeVJGA	10-Dec-02	8.5	6	548
SeVJGA	26-Dec-03	10.0	11	654
SeVJGA	04-Jan-04	9.5	11	615
SeVVJGA	23-Jun-04	11.5	6	493
SeJGA[5b]	15-Nov-04	9.0	11	452
SeVGA	26-Dec-04	12.0	6	376
Solar Probe[7]				
SeVVJGA	21-Jul-02	5.5	3.375 (EOL)	<384>
SeVVJGA	29-Jul-02	5.5	6	887
SeEJGA	05-Oct-02	5.3	5	~761
SeVJGA	07-Oct-02	5.3	5	~711
SeJGA	17-Nov-04	3.7	5	~382

1. Flight time to Jupiter for Europa Orbiter, to Pluto closest approach for Pluto-Kuiper Express, and to first perihelion pass for Solar Probe.
2. Beginning of Life (BOL) power at 1 AU.
3. Mass optimized for Delta II 7925 launch vehicle except for the following :
   ( ) indicates Delta II 7925H, < > indicates Medlite - Delta II 7325(6).
   Net spacecraft mass includes total spacecraft mass (wet) + SEP module dry mass (does not include required Xe propellent + 10% reserve) + launch adapter mass.
4. SEP parameters: LV contingency= 10%, s/c power= 250 W , different engine model, all others unchanged
5. SEP parameters: LV contingency = 10%, s/c power = 0 W , with (a) 1,2, or 3, engines running, or (b) 1,2,3 or 4 engines running, all others unchanged
6. Incomplete data; SEP parameters uncertain.
7. See Reference 5 for SEP system parameters EXCEPT for the 29-Jul-02 SeVVJGA.

sufficient performance. Figure 1 shows one such SeVVGA trajectory option which launches in March of 2004. It is interesting to note that the SeVVGA trajectory has characteristics similar to the non-SEP VVGA. The transfer types between encounters and the phasing of significant "maneuvers" are analogous. However, the low-thrust SEP system requires longer burn durations as compared to a conventional propulsion system.

The net spacecraft mass for the SeVVGA trajectory options with launch dates in 2002 and 2004 is shown in Figure 2. Figures 3 and 4 show the required Xe propellent mass and arrival V_∞ at Jupiter versus flight time for these SEP trajectories. It is important to note that higher V_∞ requirements at Jupiter would translate into higher Δv requirements on the bi-propellent system for injection into Jupiter orbit.

* All trajectory acronyms in this paper use the following key :
Se = SEP, V = Venus, E = Earth, J = Jupiter
P = Pluto, and GA = Gravity Assist
For example : SeVVJGA = SEP Venus-Venus-Jupiter Gravity Assist trajectory

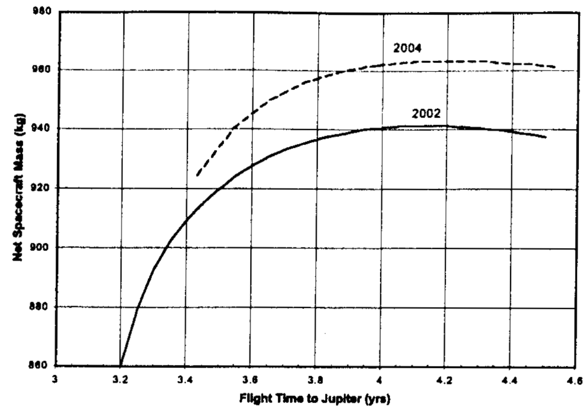

Figure 2 : Net Spacecraft Mass vs. Flight Time for Europa Orbiter SeVVGA Trajectories

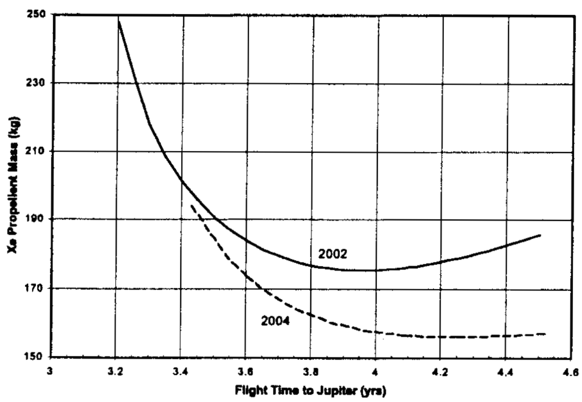

Figure 3 : Xe Propellent Mass vs. Flight Time for Europa Orbiter SeVVGA Trajectories

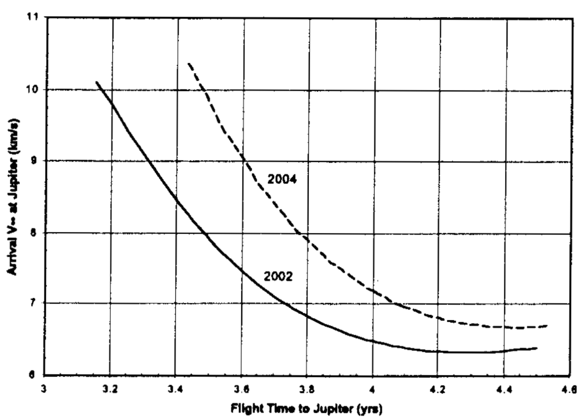

Figure 4 : Arrival V_∞ vs. Flight Time for Europa Orbiter SeVVGA Trajectories

Pluto-Kuiper Express

As stated earlier, SEP performance is highly limited by the spacecraft's distance from the Sun. Several different types of SEP trajectories, including those which take advantage of a Jupiter gravity assist, have been analyzed.

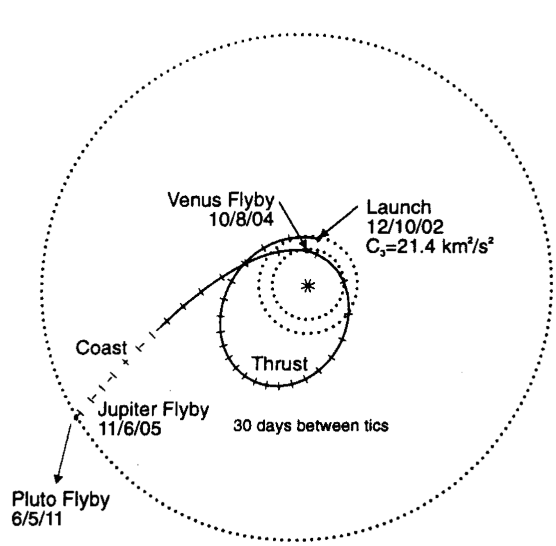

Figure 5 : Pluto-Kuiper Express 2002 SeVJGA Trajectory

These included trajectories which launch directly from Earth to Jupiter without an intermediate gravity assist (completing either less than or more than one revolution around the Sun) and those with a single or double Venus gravity assist prior to the Jupiter gravity assist. For options which launch after 2004 (when the geometry is such that Jupiter no longer provides benefit), trajectories with an Earth gravity assist in addition to those with a single or double Venus gravity assist were examined. Figure 5 shows one such SeVJGA trajectory option which launches in December 2002. Unlike the SeVVGA (Fig. 1) for Europa Orbiter, the type of transfer from Earth to Venus for the Pluto-Kuiper Express SeVJGA trajectory would not be practical when using a conventional propulsion system. In general, direct trajectories from Earth to Jupiter require higher solar array power, and a larger number of thrusters that can operate simultaneously, in order to provide a reasonable net spacecraft mass. Also, as with Europa Orbiter, trajectories which include an Earth flyby may not be desirable options.

Figure 6 shows the net spacecraft mass as a function of flight time to Pluto for VJGA and VVJGA SEP trajectories launching in 2002 and 2004. For launches in 2002, the SeVVJGA has a higher net spacecraft mass than the SeVJGA for flight times longer than about 9 years. In 2004, however, the SeVJGA outperforms the SeVVJGA over the range of flight times shown. The later date of the final Venus gravity assist for the SeVVJGA results in the use of a VJP opportunity which is later than that used by the SeVJGA launching the same year. Since a JGA is less effective on later dates, the 2004 SeVJGA outperforms the 2004 SeVVJGA. Even for launches in 2002, the additional time spent in the inner solar system by the

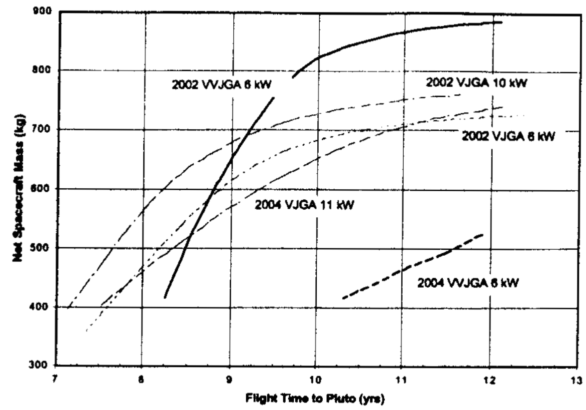

Figure 6 : Net Spacecraft Mass vs. Flight Time for Pluto-Kuiper Express SEP Trajectories

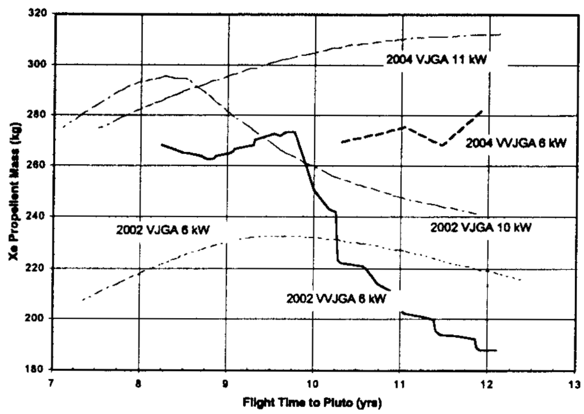

Figure 7 : Xe Propellent Mass vs. Flight Time for Pluto-Kuiper Express SEP Trajectories

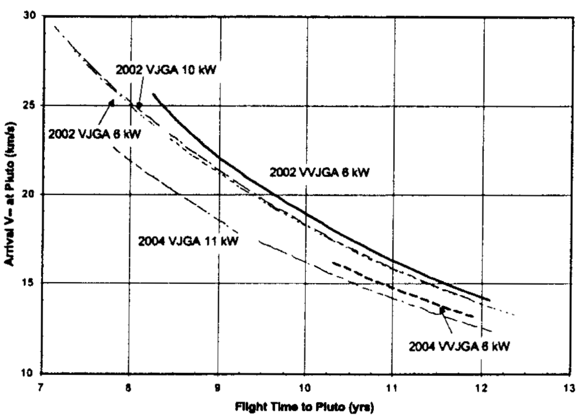

Figure 8 : Arrival V_∞ vs. Flight Time for Pluto-Kuiper Express SEP Trajectories

SeVVJGA trajectories proves to be a substantial penalty when the total flight time to Pluto is less than 9 years. Depending on total flight time, the net spacecraft mass usually increases as solar array power increases above 6 kW (at 1 AU). Figures 7 and 8 show the required Xe propellent mass and arrival V_∞ at Pluto versus flight time for these trajectories. The Pluto arrival V_∞ has a strong influence on the science encounter design. There are significant sensitivities to the spacecraft relative velocity with respect to Pluto and the requirements on spacecraft slew rate and stability.

Solar Probe

Several different types of SEP trajectories for the Solar Probe mission have been analyzed previously using a different set of engine parameters and assumptions.[6] A brief summary of these analyses and their results are included in Table 1 for completeness.

For both conventional and Solar Electric propulsion (under the constraints and assumptions already discussed), it turns out that a Jupiter flyby is enabling for a mission such as Solar Probe. Interestingly, SEP trajectories similar to the ones that use Jupiter for the Pluto-Kuiper Express mission can also be used for the Solar Probe mission. Generally, the Pluto-Kuiper Express SeVVJGA trajectories with about 12 year flight times to Pluto result in a V_∞ at Jupiter such that the spacecraft could fall back into the Sun, if the correct flyby target is chosen. Figure 9 shows what one such Solar Probe SeVVJGA trajectory may look like. The performance of these Solar Probe SEP trajectories is expected to be very similar to the corresponding Pluto-Kuiper Express SEP trajectories.

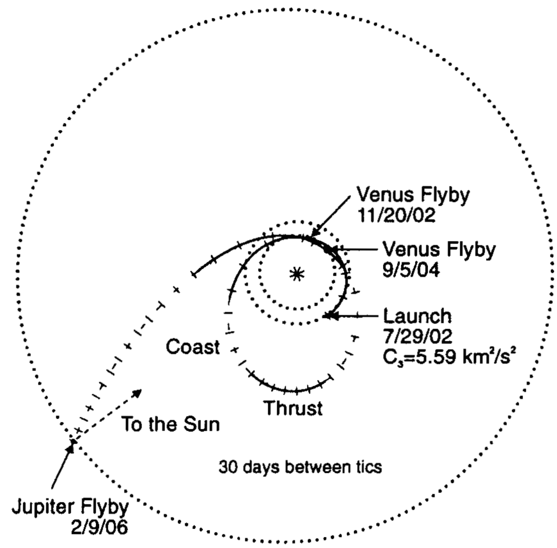

Figure 9 : Solar Pobe 2002 SeVVJGA Trajectory

CONCLUSIONS

Table 2 summarizes the highest performing SEP mission options for Ice and Fire.

Table 2 : SEP Mission Candidates for Ice and Fire

Trajectory	Launch Date (dd-mmm-yy)	Flight Time[1] (yrs)	Power Level[2] (kW)	Launch C3 (km^2/s^2)	Net Spacecraft Mass[3] (kg)	Xe Propellent[4] (kg)	Possible Spacecraft Launch Mass[5] (kg)	Delivered Mass Margin[6] (kg)
Europa Orbiter								
SeVEGA	21-Mar-04	4.8	6	3.61	1018	101	568	-427
SeEGA	08-Nov-04	4.0	6	0.68	974	217	524	-471
SeVVGA	22-Mar-04	4.2	6	3.58 (4.05)	963 (1070)	156 (171)	513 (670)	-482 (-325)
SeVGA	04-Dec-04	4.0	6	8.59	784	224	334	-661
Pluto-Kuiper Express								
SeVVJGA	15-Aug-02	9.1	6	12.31	668	266	268	23
SeVJGA	26-Dec-03	10.0	11	10.99	654	305	254	9
SeJGA[7]	12-Nov-02	12.1	11	6.68	592	424	192	-53
SeEGA	24-Jan-02	9.5	5	17.2	463	313	63	-182
Solar Probe[8]								
SeVVJGA	29-Jul-02	5.5	6	5.59	887	187	487	242
SeEJGA	05-Oct-02	5.3	5	8.4	~761	~90	~361	~116
SeVJGA	07-Oct-02	5.3	5	10.4	~711	~120	~311	~66

1. Flight time to Jupiter for Europa Orbiter, to Pluto closest approach for Pluto-Kuiper Express, and to first perihelion pass for Solar Probe.
2. Power at 1 AU BOL.
3. Mass optimized for Delta II 7925 launch vehicle except for the following :
   ( ) indicates Delta II 7925H, < > indicates Medlite - Delta II 7325(6).
   Net spacecraft mass includes total spacecraft mass (wet) + SEP module dry mass (does not include Xe propellent) + launch adapter mass.
4. Includes 10% margin on Xe propellent mass
5. Assumes dry SEP system mass of 450 kg for Europa Orbiter, and 400 kg for Pluto-Kuiper Express and Solar Probe.
6. Requirements are 950 kg delivered mass for Europa Orbiter and 225 kg delivered mass for Pluto Kuiper Express and Solar Probe. Assumes launch vehicle adapter of 45 kg for Europa Orbiter and 20 kg for Pluto-Kuiper Express and Solar Probe.
7. SEP parameters : LV contingency = 10%, s/c power = 0 W, w/ 1,2, or 3 engines, others unchanged
8. See Reference 5 for SEP system parameters EXCEPT for first trajectory listed (SeVVJGA 29-Jul-02).

Europa Orbiter

For Europa Orbiter, it is clear that the large spacecraft mass needed to accommodate the Δv requirement after Jupiter arrival significantly impacts any potential benefit of using SEP. When this study began, the early estimated mass of the Europa Orbiter spacecraft was significantly lower than what is assumed here. However, as Table 2 shows, there would still be a substantial negative delivered mass margin even with a smaller spacecraft mass requirement. A significant reduction in the required spacecraft mass (which is currently dominated by the bi-propellent propulsion system) may lead to improvements in performance when utilizing SEP.

There are several other techniques that may provide additional net spacecraft mass for these options, including increasing the solar array power, the number of operating engines, or possibly the flight time. The advantages of a Delta II launch vehicle (assuming a spacecraft plus SEP system as large as what would be required for the Europa Orbiter mission can fit within a Delta II payload fairing envelope) as compared to a launch vehicle as large as a Shuttle may be significant. However, the uncertainty in the design assumptions used for this study, as well as the cost, integration, and operational and system complexities, involved with staging a SEP system on a spacecraft as large as that of Europa Orbiter would be enormous and most likely completely overwhelm any potential benefits.

Pluto-Kuiper Express

As Table 2 shows, the Pluto-Kuiper Express mission could possibly benefit from the use of current SEP technology. The system currently being developed for the Champollion/DS4 mission may be consistent with what could be used for this mission. A reduction of flight time, from the possibly 16 years required for the reference mission on a Delta II launch vehicle, is possible. However, as with the Europa Orbiter mission, uncertainties and complexities involved with incorporating a SEP system for this mission make it unclear as to whether any overall improvement of the mission actually exists. The same improvements in flight time may be possible by launching in 2003, which provides better overall performance than the reference 2004 option, or by utilizing a slightly larger launch vehicle, such as the Delta III. The slight increase in cost here may be much more desirable than the costs of development, implimentation, integration and operation of a SEP system. Possibly, some of the alternate techniques discussed above for the Europa mission may also provide added benefit to using SEP for the Pluto mission.

Solar Probe

The potential benefits for using SEP for the Solar Probe mission are quite similar to those of the Pluto-Kuiper Express mission. As mentioned earlier, the performance of SEP missions for Solar Probe are quite similar to certain Pluto-Kuiper Express trajectories up to the Jupiter flyby. For these reasons, the same level of detail was not given to Solar Probe as was to the Europa Orbiter and Pluto-Kuiper Express SEP opportunity search. Solar Probe currently does not have the driving design issues, such as mass and flight time, that do challenge the Europa and Pluto missions. The potential enhancements of SEP, therefore, would be less significant still. And again, the small cost savings from using a Delta II launch vehicle as compared to the reference Delta III is likely to be overwhelmed by the costs and complexities involved with implementing a SEP misison. For missions such as Solar Probe, low thrust options such as solar sails may provide the performance benefits required for serious consideration, once the technology is available.

In summary, the current technology level of Solar Electric Propulsion does not appear to offer any significant performance improvements for the Ice and Fire missions. Clearly, however, the potential of this technology is tremendous. Advancements in the area of higher efficiency solar arrays and further reduction of SEP system mass may lead to further applications of this technology. The constraint on solar distance does pose a problem for missions to the outer solar system. When trying to minimize the launch system requirements, spacecraft must spend a great deal of time in the inner solar system in order to build up sufficient energy to reach the outer planets. The potential of electric propulsion beyond the constraints of the sun (i.e. nuclear electric propulsion) could be significant.[7] Perhaps one day in the not so distant future, electric propulsion will truly open the outer solar system to human exploration as well as other scientific missions.

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